

Visual Word Processing in the Context of Learning to Read

Thesis

(cumulative thesis)

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To my Reto for his incredible patience, understanding and support
To Krzyś for his sense of humor and the right word in every situation
To Mom and Dad for their believe in me, their enthusiasm and optimism

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Summary

In the course of reading acquisition children learn to recognize orthographic patterns and link them to the corresponding phonological and semantic counterparts. Thus, successful recognition of visual word forms is the foundation of reading.

Longitudinal data from children at the end of 1st grade and one year later in 3rd grade was collected. Moreover, a group of adults was investigated. The results from study 1 demonstrated the presence of print tuning in the 1st year of reading acquisition and its development at the individual level. Moreover, individual differences in print tuning were related to word-reading fluency and semantic knowledge, but not to measures of phonological processing, indicating that top-down modulation of print tuning is rather of semantic than phonological nature. The event-related EEG analysis of the N1 phases in study 2, revealed early effects related to print tuning and late effects related to lexical processing in adults, but not in children. Hence, study two proposes a sequential mode of visual word processing during the N1 latency range in adult readers, with bottom-up tuning preceding the interactive top-down modulation.

Zusammenfassung

Im Verlauf des Lesenlernens lernen Kinder, orthographische Muster zu erkennen und diese mit den dazugehörigen phonologischen und semantischen Gegenstücken zu verbinden. Somit ist die erfolgreiche Wiedererkennung von visuellen Wortformen die Grundlage des Lesens. Es wurden Kinder am Ende der 1. Klasse und ein Jahr später in der 3. Klasse untersucht. Zusätzlich wurden Daten einer Gruppe von Erwachsenen erhoben. Die Resultate von Studie 1 zeigten das Vorhandensein von Print Tuning bereits im ersten Jahr des Lesenlernens und zusätzlich die Entwicklung von Print Tuning auf individueller Ebene. Es konnte zudem gezeigt werden, dass diese individuellen Unterschiede im Print Tuning mit Wortleseflüssigkeit und semantischem Wissen assoziiert sind, nicht aber mit phonologischer Verarbeitung. Dies deutet darauf hin, dass die Top-down Modulierung von Print Tuning eher semantischer als phonologischer Natur ist. Die ereigniskorrelierte EEG-Analyse der N1 Phasen bei Erwachsenen in Studie 2 zeigte, dass frühe Effekte mit Print Tuning und späte Effekte mit lexikalischer Verarbeitung assoziiert sind. Während bei Kindern keine lexikalischen Effekte gefunden wurden, konnte robustes Print Tuning sowohl im frühen als auch im späten N1 Zeitfenster nachgewiesen werden. Die zweite Studie schlägt daher einen sequentiellen Modus der visuellen Wortverarbeitung während des N1 Zeitfensters bei Erwachsenen vor, mit vorangehendem Bottom-up Tuning und nachfolgender interaktiver Top-down Modulierung.

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Abbreviations

ANOVA – analysis of variance

BAKO – Basiskompetenzen für Lese-Rechtschreibleistungen

BESA – Brain Electrical Source Analysis software

EEG – electroencephalography/electroencephalogram

ERP – event-related potential

GFP – global field power

Hz – hertz

IQ – intelligence quotient

M – mean

MEG – magnetoencephalography/magnetoencephalogram

ms – milliseconds

N – number of subjects

N1 – N1 component of the ERP

P1 – P1 component of the ERP

SD – standard deviation

SLRT-I – Salzburger Lese- und Rechtschreibtest, 1st edition

SLRT-II – Salzburger Lese- und Rechtschreibtest, 2nd edition

SLS – Salzburger Lese-Screening für die Klassenstufen 1-4

HAWIK-IV – Hamburg-Wechsler-Intelligenztest für Kinder - IV

RAN – rapid automatized naming

VWFA – visual word form area

y – years

μV – microvolt

1. Introduction

Reading is a fundamental process of literacy acquisition that is acquired through explicit schooling (Abutalebi et al., 2007). In Switzerland, formal reading and writing instruction starts at the beginning of primary school education (i.e. 1st grade at approximately 7 years of age). Meanwhile, the recent trend towards early education of English as a foreign language has prompted the policy makers of numerous European countries to introduce early (primary school level) exposure of English. To account for this general trend, there has been a recent shift in the Swiss educational system towards teaching two foreign languages already at the primary school level (EDK, 2004). As a consequence, second grade children (~8 years) in the canton of Zurich start learning English as a foreign language. The idea behind this early exposure of English is to familiarize young children with the language, leaving formal, explicit instruction of grammatical rules to secondary school level. Hence, in this early English training primary focus is directed towards basic communication skills and comprehension of short written and spoken texts (Graf-Beglinger, Stotz, & Keller-Bolliger, 2009).

This thesis was embedded in a larger project entitled *“Neural basis of individual differences in foreign language learning in school: effects of dyslexia and immigration”* which was supported by the Swiss National Science Foundation. Overall, longitudinal data from children at the end of 1st grade (7.5 years, $N = 113$) and one year later in 3rd grade (8.9 years, $N = 107$) was collected. Additionally, a group of adult participants (25.1 years, $N = 22$) was investigated. Each participant took part in a behavioural and an EEG session. The project was based on the assumption that the learning process and the corresponding organization at the neural level rely upon various individual factors such as reading performance and bilingualism. The long-term goal of the study was to provide better understanding of the brain processes that underlay difficulties not only in native but also in foreign language learning and to develop strategies that would support early recognition of children at risk and assign them to specifically targeted trainings. Thus, the present thesis focuses on early visual word processing in the context of learning to read.

1.1. Electroencephalography (EEG) – a modern imaging method

In 1929 in a series of experiments, Hans Berger demonstrated a method how to measure the electrical activity of the human brain by placing an electrode on the scalp, amplifying the signal and plotting the changes in voltage over time (Luck, 2005). This electrical activity is called the electroencephalogram or EEG. As of today, EEG is a widespread and validated noninvasive tool to observe temporal dynamics of the brain's network activity during a wide variety of processes.

1.1.1. Generation of signals

There are two main types of electrical activity generated within the brain, i.e. action potentials and postsynaptic potentials. Action potentials are discrete voltage spikes that travel down the axon to the synapses where neurotransmitters are released. Postsynaptic potentials are voltages that arise when neurotransmitters bind to their receptors on the postsynaptic cell membrane (Luck, 2005). If an electrode is placed in the intracellular space of a living brain both types of electrical activity can be recorded. As for EEG, where the electrodes are placed on the scalp, only the postsynaptic electrical activity of the perpendicularly aligned (with respect to the cortex surface) pyramidal cells can be measured (Luck, 2005). These postsynaptic potentials are summed up and passively propagated to the scalp (Gazzaniga, Ivry, & Mangun, 2002; Roth, Ford, Pfefferbaum, & Elbert, 2000). It is due to volume conduction that makes it possible to record electric voltages with the use of electrodes placed on the head surface (Hauk, 2008; Luck, 2005; Roth et al., 2000). The voltage distribution is blurred as electrical potentials spread out while travelling through the brain. Moreover, as soon as they arrive at the skull, they disperse laterally due to the high resistance of the skull. Thus, the voltage measured on the scalp surface depends on both the orientation and position of a generator dipole, but also on the thickness of a skull and a scalp (Luck, 2005).

Due to its magnificent temporal resolution and relatively inexpensive application, EEG recordings became very popular in the study of language as they allow observation of the brain's activity to a particular

linguistic stimulus. The use of event-related potentials (ERPs), which reflect the brain's response to a given stimulus, allows analyzing differences in size, distribution and timing of neural activity across the scalp for different experimental conditions (Handy, 2005).

1.1.2. Event-related potentials

ERPs are neural signals of about 5 μ V (Hauk, 2008) that are generated in the brain in response to a specific event, hence are fixed to a specific time segment. In an EEG experiment, trials are presented repeatedly and ERPs are extracted from a raw EEG file. Data before and after a specific external event is averaged across all trials at the very same time frame (epoch) resulting in a time-locked signal that is plotted as waveforms for each recording electrode (Brandeis & Lehmann, 1986; Gazzaniga et al., 2002). The waveforms' peaks and troughs correspond to components of the ERP (Brandeis & Lehmann, 1986; Gazzaniga et al., 2002). Component labeling typically refers to its polarity (positive versus negative) and latency of occurrence within the ERP waveform. As such, the N1 component of the event-related potential refers to the first measurable negative potential (Hauk, 2008; Luck, 2005). Nonetheless, labeling can vary and the visual N1 component is often referred to as N170 due to its typical occurrence at about 170 ms. Notably, components of different modalities can be labeled in the same way without being functionally related to each other (e.g., visual and auditory P1 and N1; Luck, 2005). Most importantly, ERPs do not only provide information about temporal changes in response to a specific event, but also indicate the strength of the electrical activity measured. As such, topographic voltage maps can be derived to visualize how the distribution of positive and negative fields on the scalp changes over time. The isopotential lines of the topographic maps join the electrodes with similar measurement values. Voltages indicating positivity and negativity of the measured activity are traditionally illustrated in blue (negativity) and red (positivity). The color intensity increases respectively as the voltage differs from zero (Michel & Brandeis, 2009). The global field power (GFP) can be calculated to determine the overall strength of a scalp field potential. Here, the field's activity is measured

at every time point and all electrodes are considered equally. The squared potential differences between all recording electrode pairs are averaged and a reference-independent measure of the scalp field is obtained (e.g., Koenig, Kottlow, Stein & Melie-García, 2011).

There are two main approaches for ERP analysis, which can be conducted either at a single electrode or across electrode clusters. In the first approach, the ERP response is analyzed at a peak of a given component (e.g., N1) with respect to its amplitude (absolute or local, based on visual inspection or automatic detection; Keil et al., 2014) and/or latency (e.g., Kast, Elmer, Jancke, & Meyer, 2010). In the second approach, instead of accounting for the value on an individual peak, the mean value of a given time interval (i.e. time segment) that corresponds to a latency of a particular component (e.g., N1) is analyzed (e.g., Brem Lang-Dullenkopf, Maurer, Halder, Bucher & Brandeis, 2005). Importantly, in the mean segment interval approach the ERP response can be investigated either across the entire latency range (e.g., Brem et al., 2005; Mahé, Bonnefond, Gavens, Dufour, & Doignon-Camus, 2012; Maurer et al., 2006), or subsequent smaller time windows can be derived from a given time range (e.g., early N1 response and late N1 response, see Brem et al., 2006; Nemrodov, Harpaz, Javitt, & Lavidor, 2011). Such a subdivision provides a more comprehensive understanding of the temporal dynamics within a given component as different processes can coincide within typically long components such as N1 or P300.

Although not yet a common practice in EEG studies, it is also possible to investigate a given component of the ERPs not only on the group level but also on the individual subject level by taking the individual trial-to-trial variance into account.

1.2. The phenomenon of reading

In order to understand the written language we need to decode the visual patterns that we are confronted with on everyday basis (Dehaene, Cohen, Sigman, & Vinckier, 2005). We live in a literate society where reading is essential for successful mastery of daily situations. Hence, learning to read is a fundamental step in literacy

acquisition (Abutalebi et al., 2007). The ability to identify the word's phonological components and associating them with their orthographic counterparts is the key to the process of learning to read (for review see Ehri, 2005). Importantly, while some children learn to read without significant problems, others face substantial difficulties (National Center for Education Statistics, 2011). Reading skills can be defined by a continuum with excellent readers at one extremum end and dyslexic readers at the other extremum. An individual scoring below the lowest 10 percent of the population is typically referred to as dyslexic (e.g., Maurer et al., 2007a), whereas individuals scoring at the lower 20 or 25 percent of the population are often assigned to as poor readers (e.g., Brem et al., 2013).

1.2.1. The dual route for reading

Information-processing models describe reading as a series of cognitive processes including the visual analysis of letters and letter strings, the processing of word forms, the conversion of graphemic word forms into corresponding phonological word forms, and finally the access to the corresponding semantic representations. Coltheart's (2007) dual model of reading proposes that single-word reading may be carried out in two distinct ways i.e. through a lexical and a non-lexical route. The lexical or "direct" pathway is involved in recognition of familiar, real words. The representations of these words are being stored in a mental lexicon containing information about word spellings and pronunciations. On the other hand, the non-lexical or "indirect" pathway makes no reference to the mental lexicon but converts the orthographic word forms (graphemes) into their corresponding phonemes (grapheme-to-phoneme conversion, GPC; Coltheart, Curtis, Atkins, & Haller, 1993). This "indirect" route is used to decode unfamiliar letter strings, with unfamiliar meanings. Importantly, skilled reading relies upon the use of both lexical and non-lexical pathways, as the non-lexical pathway may enhance the process of the lexical route when a reader is confronted with frequent, familiar words (Coltheart, 2007).

1.2.2. Visual word recognition

Lupker's interactive model of visual word recognition (2007) assumes that the components of word recognition systems interact with each other in a way that mental representations of orthographic, phonological and semantic structures activate and inhibit each other while words are being processed. The activation of orthographic units in word reading is transmitted to further units such as phonology and semantics, while simultaneously a feedback loop is generated that flows back to the units that were initially activated. The relationship between orthography, phonology and semantics is enhanced through the process of learning, so that for successful reading a dynamic interplay between all the three components of visual word recognition is implemented.

1.2.3. Reading network and N1 specialization for print

Recent advances in psychology and neuroscience have begun to unravel the principles that underlay the brain's reading circuits. Modern brain imaging methods demonstrated that the literate adult brain contains specialized cortical mechanisms that are exquisitely attuned to the recognition of printed words (Dehaene et al., 2005).

Whenever readers are confronted with written words, a cortical network in the left occipito-temporal cortex is activated (Cohen et al., 2002) that allows fast and effortless recognition of visual word forms. This visual word form area (VWFA) that develops as an outcome of progressive specialization for word forms was proposed to be a center for visual word recognition, playing an essential role in the visual analysis of letters and word shapes (Cohen & Dehaene, 2004). The N1 or N170 component of the ERP (peaking at around 150 to 200 ms after the stimulus onset) has been consistently reported to show pre-lexical sensitivity to orthographic versus non-orthographic strings (e.g., Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Gros, Doyon, Rioual, & Celsis, 2002; Maurer, Brem, Bucher, & Brandeis, 2005a) presumably linked to the VWFA (Brem et al., 2006). Displaying posterior negativity and fronto-central positivity, it follows the first positive component (P1) of the ERP and originates from bilateral, but typically left lateralized occipito-temporal regions (e.g., Bentin et al., 1999; Brem

et al., 2005; Brem, Halder, Bucher, Summers, Martin & Brandeis, 2009; Parviainen, Helenius, Poskiparta, Niemi, & Salmelin, 2006; Tarkiainen, Helenius, Hansen, Cornelissen & Salmelin, 1999).

N1 print tuning has been proposed to be a marker indicating specialization for print (also termed 'coarse neural tuning for print'; Maurer et al., 2006), as it shows robust amplitude differences in processing familiar words and unfamiliar symbol strings in adults (e.g., Bentin et al., 1999; Brem et al., 2005; Brem et al., 2009; Maurer, Brandeis, & McCandliss, 2005b; Tarkiainen et al., 1999) as well as in literate children (e.g., Araújo, Bramão, Faísca, Petersson, & Reis, 2012; Brem et al., 2009; Maurer et al., 2006; Maurer et al. 2007a; Parviainen et al., 2006). However, in studies that used false-font strings as a control condition the word-specific print tuning effects were less consistently found, possibly due to better control for low-level visual differences. Interestingly, while false-font studies with adult participants do not always reveal robust print tuning effects (Eulitz et al., 2000; Schendan, Ganis, & Kutas, 1998; Wong, Gauthier, Woroch, DeBuse, & Curran, 2005; Xue, Jiang, Chen, & Dong, 2008), studies with children consistently indicated stronger activation to words than to false-font strings (Brem et al., 2010; Hasko, Groth, Bruder, Bartling, & Schulte-Körne, 2013).

1.2.4. N1 lexicality effects

Contrary to more robust findings on N1 print tuning, the findings on lexicality effects are equivocal with some studies indicating a significant difference between words and pronounceable pseudowords in adult participants (Hauk, Davis, Ford, Pulvermuller & Marslen-Wilson, 2006b; McCandliss, Posner & Givon, 1997) and other studies finding no such differences in neither children nor adults (Araújo et al., 2012; Bentin et al., 1999; Kast et al., 2010). Such inconsistent results might derive from an array of different factors some of them being related to task demands (e.g., passive vs. active, perceptual vs. lexical), stimulus presentation parameters (e.g., short vs. long duration, masked vs. unmasked; Xue et al. 2008), development (Maurer et al., 2006) or the degree of orthographic transparency (Maurer et al., 2005b). It is also possible that

the less robust lexicality effects are difficult to grasp when averaging across the typically lengthy N1 time segment.

1.2.5. Development of N1 print tuning with learning to read

When learning to read, fast visual brain processes are recruited that allow rapid recognition of familiar orthographic patterns. As such, the N1 print tuning that was absent in non-reading kindergarten children (Maurer et al., 2005a), emerged after a short grapheme-phoneme training (Brem et al., 2010), but was consolidated only after two years of formal reading instruction (Maurer et al., 2006). Development of the N1 print tuning has been shown to follow an inverted u-curve with an initial amplitude increase and its subsequent decrease in experienced adult readers (Brem et al., 2009; Maurer et al., 2006). Moreover, major developmental changes related to visual processing have been reported for various ERP components. As such, longer latencies and larger amplitudes were often reported for children compared to adults (e.g., Grossi, Coch, Coffey-Corina, Holcomb, & Neville, 2001).

1.3. Conclusions

Learning to read is a major step in child development. To date, the development of N1 print tuning has been extensively studied at the group level (e.g., Araújo et al., 2012; Brem et al., 2009; Brem et al., 2010; Maurer et al., 2006; Maurer et al., 2007). However, not many studies investigated this neural correlate at the individual response level (Parviainen et al., 2006). Moreover, regarding the fact that N1 specialization for print occurs early in the course of learning to read (Brem et al., 2009; Brem et al., 2010; Maurer et al., 2005a; Maurer et al., 2007a), it seems critical to understand this process and its underlying cognitive mechanisms at the initial stages of learning to read. Once such cognitive mechanisms related to print tuning are elucidated, not only will we understand the mechanisms of learning to read better, but also understand why some children face difficulties at the beginning of reading training.

Importantly, while print tuning was robustly found in studies that used simple geometric forms as a control condition (i.e., symbol strings, e.g.,

Bentin et al., 1999; Brem et al., 2005; Maurer et al., 2006), the results of studies using false-font characters (i.e., false-fonts; Eulitz et al., 2000; Schendan et al., 1998; Wong et al., 2005; Xue et al., 2008), which are better matched for low-level visual differences, are less clear, and so far have never been studied in children and adults within the same experimental design. Also, the findings on lexicality effects are much less robust and not consistently found. As the N1 component has a typically long latency range and previous literature indicated that there are several processes coinciding within its time range (e.g., Brem et al., 2006; Cohen et al., 2000; Nemrodov et al., 2011), it is possible that the less robust lexicality effects are difficult to capture when averaging across the entire N1 time window. Furthermore, it has been suggested that the lexicality effects are more prominent at the initial stages of learning to read as they were found in 2nd grade children but not in adults (Maurer et al., 2006). Therefore, investigating a young population of children in a longitudinal fashion and comparing them to adults could provide important insights not only with respect to the temporal dynamics of basic visual processes at the early stages of learning to read, but might also contribute to our understanding of the development of both print tuning and lexicality effects.

2. Neurocognitive mechanisms of learning to read: print tuning in beginning readers related to word-reading fluency and semantics but not phonology¹

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3. Temporal dynamics of early visual word processing - early versus late N1 sensitivity in children and adults^{II}

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4. General Discussion

Given the inevitable role of reading skills in modern society, the question how children learn to read has gained large interest (e.g. Nation & Snowling, 2004; Pennington & Lefly, 2001; Puolakanaho et al., 2008; Ricketts et al., 2007; Vellutino et al., 2007). Due to recent advances in the study of cognitive neuroscience, we become gradually aware of the complexity of the neural mechanisms that underlay reading. Recent electrophysiological studies point to the importance of the N1 event-related potential in reading. Hence, the present thesis examined the developmental course of the N1 component, its underlying cognitive mechanisms and its temporal dynamics. The first study demonstrated the presence of print tuning in the first year of reading acquisition both on the group, as well as the individual level. Moreover, it could be shown that individual differences in print tuning are related to word-reading fluency and vocabulary knowledge, but not to measures associated to phonological processing. As such, it seems that at the early stages of learning to read print tuning is influenced by semantic rather than phonological top-down modulations. In the second study print tuning was found in the early and late N1 in both 1st and 3rd graders, while in adults it could be detected only in the early N1. Moreover, in the absence of lexicality effects in 1st and 3rd grade children, the late adult N1 indicated differential processing of familiar words and unfamiliar pseudowords. Hence, results from study two suggest that bottom-up tuning precedes interactive top-down modulations during visual word processing, yet such temporal dynamics would develop only later in the course of reading acquisition.

4.1. Learning to read and the N1 print tuning effects

A previous study has shown that the N1 print tuning that was absent in illiterate kindergarten children had emerged after two years of formal reading training at school (Maurer et al., 2006). Importantly, it has been suggested that already short grapheme-phoneme training can induce the print-specific N1 response in non-reading kindergarten children, which declines after discontinuation of the training (Brem et al., 2010). At the same time, Parviainen et al., (2006) reported that only slightly

more than half of the assessed 1st graders exhibited the presence of print tuning. Contrary to these findings, in both study one and study two robust print tuning was found in a sample of 1st grade children. Most importantly, in study one the print tuning effects were not only indicated by the overall larger amplitudes to German words compared to false-font strings and by shorter peak latencies for false-font strings compared to German words at the group level, but the print tuning effects have also been robustly found at the individual response level. As such, 88.2% of the assessed 1st graders exhibited presence of print tuning. Interestingly, children who lacked print tuning were disproportionally more often found amongst poor than normal readers, suggesting that the absence of print tuning might be associated with poor reading performance.

Despite the better control for low-level visual differences with the use of false-font strings, print tuning was robustly found for the populations of children in both study one and study two. This suggests that the print tuning effects revealed by previous studies with children that used symbol strings as a control condition (e.g., Araújo et al., 2012; Brem et al., 2009; Maurer et al., 2006; Maurer et al., 2007a) were not due to low-level visual differences (see also Brem et al., 2010; Brem et al., 2013; Hasko et al., 2013). Importantly, while robust print tuning effects have been consistently reported for adults when symbol-strings were used as a control condition (e.g., Bentin et al., 1999; Brem et al., 2005; Maurer et al., 2005b; Tarkiainen et al., 1999) this was not always true when a false-font condition was applied (e.g., Schendan et al., 1998; Xue et al., 2008). For adults, study two revealed robust print tuning effects only in the early, but not in the late N1 segment. Hence, it seems that the subdivision of the N1 segment allowed us to grasp the finer word-false-font differences that were possibly missed in some previous studies (e.g., Schendan et al., 1998; Xue et al., 2008). This two-phasic N1 in adults with larger amplitudes to words compared to false-font strings in the early segment and the reversed pattern in the late segment may reflect the influence of expertise on visual processing. Hence, the adult's extensive reading experience appears to enhance faster recognition of familiar visual patterns and thus, leads to early activation

in response to words within the N1 component. On the other hand, the later phase of N1 would correspond to other processes, such as lexical validity (discussed below).

4.1.1. Cognitive underpinnings of N1 print tuning

Study one also investigated the association between N1 print tuning and various cognitive reading components in a sample of 1st grade children with a wide range of reading skills. It was found that more fluent word reading was associated with larger print tuning. However, the largest part of the entire variance in print tuning was explained by a combination of word-reading fluency and vocabulary. The association between word-reading fluency and N1 print tuning concurs with previous findings indicating reduced print tuning in dyslexic children (Araújo et al., 2012; Maurer et al., 2007a) as well as adults (Helenius et al., 1999; Mahé et al., 2012). Most importantly, study one extends these findings by showing that this result is not only valid for a clinical population. As such, word-reading fluency is proposed to be a stable measure to explain print tuning in the first school year, even across children ranging from very poor to most fluent readers. Given the role of phonology in theories of reading (Ehri et al., 2011) and dyslexia (Bradley et al., 1978) it seems surprising that none of the measures reflecting phonological processing contributed to the variance in print tuning. A recent model implementing a predictive coding framework for reading (Price & Devlin, 2011) proposed that top-down phonological and semantic predictions interact with bottom-up visual input in the ventral occipito-temporal (vOT) cortex. While N1 print tuning has been associated with word-specific processes in the VWFA in the vOT (Dehaene et al., 2005), study one suggests that at the early stages of learning to read, such predictions are derived from semantic rather than from phonological information.

4.2. N1 lexicality effects

While a previous study using an implicit reading task reported N1 lexicality effects for 2nd grade children (Maurer et al., 2006), no robust lexicality effects were found in study one with younger 1st grade

children. Also study two, that investigated N1 lexicality effects in both 1st as well as in 3rd grade children, could not demonstrate a presence of this effect (neither in the early nor in the late N1 segment). As this effect was found in the late N1 segment in adult participants, it seems plausible that the language-related processes might not yet be entirely established in the sample of 1st and 3rd grade children investigated in both studies. Indeed, lexicality effects were not always robustly found in studies with children (Araújo et al., 2012; Kast et al., 2010). Importantly, the weaker N1 lexicality effect that has been found in adults for the English word versus pseudoword comparison is in agreement with another study that reported less pronounced N1 lexicality effects in the non-native languages as compared to the native language (Proverbio et al., 2009).

Presumably, due to faster recognition of familiar visual patterns and enhanced early activation to words during the N1 component, adult readers exhibited N1 print tuning effects in the early N1 segment. At the same time, the lexicality effects that were found in the late N1 suggest that higher-level language processes modulate the late N1 activation for words, while processing of unfamiliar word forms seems to be less modulated by higher-level processes. The distinctive developmental effects for the early and late N1 segments suggest different processes coinciding within the N1 latency range (see also Brem et al., 2006; Nemrodov et al., 2011), which are evident in older and more experienced readers.

Taking the results of the N1 print tuning and lexicality effects together, study two proposes a sequential mode of visual word processing during the N1 time range in experienced readers. The increased activation in response to words in the early N1 would reflect neural tuning for print underlying visual expertise for letter strings, while the late N1 would correspond to visual word processing that is influenced by the linguistic top-down modulation. In the context of implicit reading such linguistic-top down modulations would lead to increased activation for words compared to pseudowords. In this sense, the early N1 segment would correspond to the neural tuning for visual word properties (Dehaene et al., 2005), while the late N1 would correspond to the interactive mode of

orthographic processing, where the visual processes are influenced by the linguistic feedback mechanisms (Price & Devlin, 2011).

4.3. Developmental effects

The electrophysiological data from study two revealed development-related changes in the lateralization pattern for both N1 print tuning as well as lexicality effects. A clearly left-lateralized adult N1 was found in response to all alphabetic conditions, which concurs with previous studies (e.g., Bentin et al., 1999; Brem et al., 2005; Maurer et al., 2005a, Tarkiainen et al., 1999). Furthermore, the enhanced left-lateralization of German words compared to false-font strings in the print tuning analysis might rely upon the left-hemispheric specificity in letter string processing. It has been suggested that such word specific N1 lateralization develops progressively with increasing reading skills (e.g., Brem et al., 2013; Maurer et al., 2005a; Maurer et al., 2006). Indeed, study two indicates that such a specialization emerges early in the course of learning to read, given the rather right-lateralized print tuning effects in 1st grade children which became more left-lateralized already in 3rd grade children.

In agreement with previous literature (Brem et al., 2006; Brem et al., 2009; Grossi et al., 2001; Holcomb et al., 1992; Kok & Roijakkers, 1985; Maurer et al., 2005a; Maurer et al., 2006), study two reported age-related decrease of overall amplitudes and segment latencies for both N1 print tuning and lexicality effects. Decreasing latencies have been associated with generally enhanced processing speed in neural networks (Brem et al., 2006) possibly reflective of more efficient connectivity and specific structural alternations, such as ongoing myelination of fiber tracts and reductions in grey matter density associated with maturation (Sowell et al., 2004). On the other hand, the general attenuation of amplitudes may reflect changes in the skull's volume conduction as well as changes in functional organization that becomes more focal and fine-tuned with age (Casey et al., 2005).

4.4. Conclusions and outlook

4.4.1. Print tuning

Study one investigated N1 print tuning and its underlying cognitive components at the early stage of reading acquisition. Although word-reading fluency was shown to be associated with print tuning, a large part of the variance remained unexplained. While some of this variance could be attributed to semantic knowledge, further studies are needed to identify additional factors that influence print tuning.

Contrary to Parviainen et al. (2006), study one found robust print tuning effects already after one year of formal reading training. While this discrepancy in results might be due to early stages of print tuning that are possibly dominated by radial sources for which EEG is more sensitive than MEG, it would be interesting to investigate the developmental course of print tuning with the use of both EEG and MEG within the exact same experimental paradigm. Such an experimental set up would help clarifying whether the absence of print tuning in young readers (Parviainen et al., 2006) and its presence in adults (Tarkiainen et al., 1999) in MEG studies can be attributed to the specificity of the neuronal sources that contribute to print tuning effects at different developmental stages.

Given the lack of print tuning that was disproportionally more frequently found amongst poor than normal readers, it would be interesting to investigate the N1 latency onset of print tuning preferably in a large group of young children with a wide range of reading skills, ideally in a longitudinal fashion. Such a study design would help clarify whether poorer readers really lack print tuning, or alternatively that they do exhibit it, but only at later latencies. Such a delay in the onset of print tuning would correspond to the poor reader's delayed reading speed.

4.4.2. Lexicality effects

Regarding the contradictory results that are found in the N1 lexicality literature, future studies on the lexicality effect shall target an array of specific factors that potentially contribute to these inconsistencies, such as the influence of experimental tasks (passive vs. active), stimuli presentation mode (blocked vs. randomized), words' orthographic

opacity (shallow vs. transparent) as well as developmental stage (children vs adults). Moreover, special care should be taken when designing the pseudoword stimuli. Ideally, pseudowords shall match the word stimuli in the closest way possible (corresponding bigram frequencies and neighborhood size need to be specifically addressed). Considering the lack of lexicality effects in 1st as well as 3rd grade children in study two, it would be valuable to investigate the same cohort of children in higher grades (e.g., 5th or 6th grade). This would help clarifying whether the absence of lexicality effects in both the native and the foreign language was due to not yet entirely established reading systems. Moreover, a longitudinal study comparing children that undergo standard English training (i.e., two lessons of English per week) with children that participate in immersive programs of foreign language learning would allow to draw conclusion on how much exposure is needed to facilitate the N1 lexicality response in the acquired foreign language.

Altogether, the present thesis provides valuable insights into early visual word processing, its temporal dynamics and underlying cognitive mechanisms. Moreover, it indicates that in order to gain a broader picture on the individual variation of the effects investigated; future studies shall take into account not only the group averages but also the individual trial-to-trial variance. Such approaches would provide a more comprehensive understanding of the individual distribution of the investigated phenomena.

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Curriculum Vitae

Aleksandra Eberhard-Moscicka

Year of birth 1986
Nationality Polish

Profile

In my research I investigate neural and cognitive processes of learning to read at an early stage of reading acquisition. With the use of electroencephalography (EEG) and behavioral measurement tools, I am studying brain correlates of reading development in typical and atypical children, as well as possible markers of developmental dyslexia. I am expressly curious on determining the neural basis underlying language mechanisms and cognitive disorders deriving from them.

Education

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| 2010/15 | Doctoral position University of Zurich, Switzerland Diploma thesis: Visual word processing in the context of learning to read Affiliation: Cognitive Neuroscience Advisors: Prof. Dr. Urs Maurer, Prof. Dr. Volker Dellwo, Dr. Silvia Brem PhD programs: PhD Program, Psychology, University of Zurich; ZNZ International PhD Program in Neuroscience, Swiss Federal Institute of Technology ETH & University of Zurich |
| 2010 | Master of Arts in Psychology <i>with first class honours</i> University of Wroclaw, Poland; in collaboration with University of South Wales, Great Britain Diploma thesis: Manner of language acquisition and the visual laterality effect amongst Swiss bilinguals Affiliation: Neuropsychology Advisors: Dr. Krystyna Weglowska-Rzepa and Prof. Dr. Maria Stras-Romanowska |
| 2009 | Bachelor of Science in Psychology <i>with first class honours</i> University of South Wales, Great Britain |

Diploma thesis: Age of acquisition and the visual laterality effect in word recognition among Polish and German bilinguals
 Affiliation: Neuropsychology
 Advisors: Dr. Peter Mayer and Dr. Martin Graff

Internships

- 2009 Forensic Psychiatric Hospital
 Wroclaw, Poland
 Position: Assistant of forensic psychologist
 Responsibilities: Supervised psychological assessment of forensic patients with use of methods such as WAIS-R test, Raven's Progressive Matrices, MMPI, Benton Visual Retention Test, Bender Visual-Motor Gestalt Test, Rey-Osterrieth Complex Figure, Rorschach Test, Koch's Tree-Drawing Test, Cattell's 16 Factor Test, NEO-FFI and psychological interview.
- 2007/08 Neuropsychological laboratory
 Wroclaw, Poland
 Position: Assistant of speech therapist and neuropsychologist
 Responsibilities: Program preparation and supervised interaction with groups and individuals of aphasic children and adolescence, writing reports from group and individual meetings with patients.

Teaching

- 2011/14 Practical part of the seminar: Topography-based analyses of EEG/ERP data, Department of Psychology, University of Zurich
- 2011/13 Supervision of master students that completed their theses within my PhD project, Department of Psychology, University of Zurich

Invited talks

- 2013 Moscicka, A. K., & Jost, L. B. Anatomy of the Human Brain and Research in Cognitive Neuroscience. Master of Advanced Studies (MAS) in Schulpsychologie, University of Zurich

2012 Moscicka, A. K., & Jost, L. B. Reading in the Brain.
English Department, University of Zurich

Conference poster presentations

2014 Cognitive Neuroscience Society, CNS
Boston, MA
First Zurich Computational Psychiatry Meeting
Zurich, Switzerland

2013 Cognitive Neuroscience Society, CNS
San Francisco, CA
International Conference on Basic and Clinical
Multimodal Imaging, BACI
Geneva, Switzerland
Swiss Psychological Society, SSP
Basel, Switzerland
Donders Discussions
Nijmegen, Netherlands

2012 Brain Fair - "Brain and Technology"
Zurich, Switzerland
Organization for Human Brain Mapping, OHBM
Beijing, China

Publications

Eberhard-Moscicka A. K., Jost L. B., Raith M., & Maurer U. (2015) Neurocognitive mechanisms of learning to read: print tuning in beginning readers related to word-reading fluency and semantics but not phonology. *Developmental Science*, 18(1), 106–118

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